The Electroweak Phase Transition and Precision Higgs Physics

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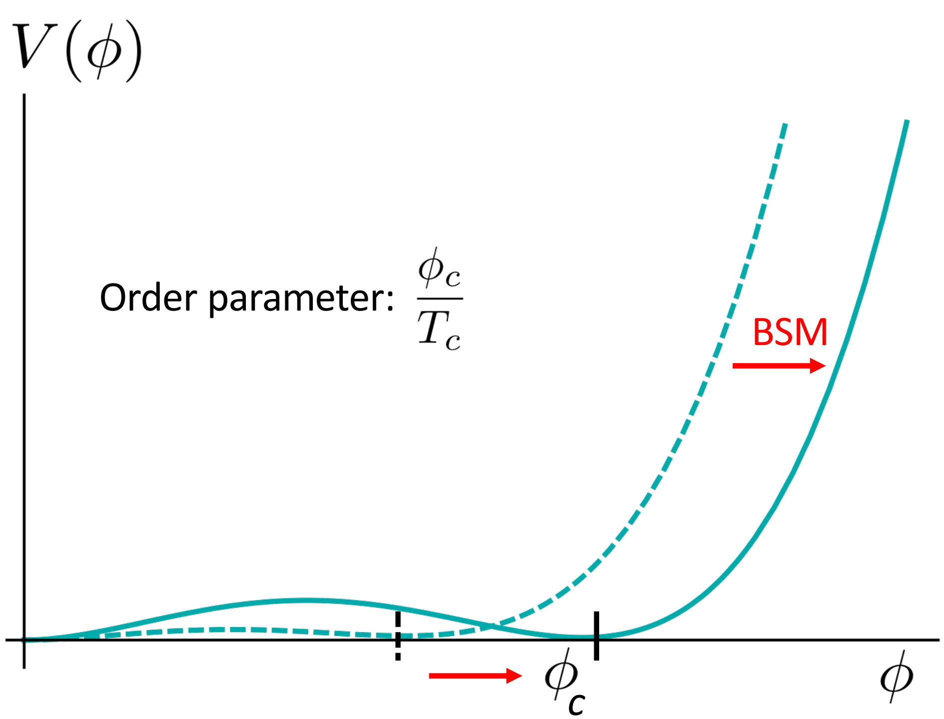
Motivation

Determining the nature of the electroweak phase transition is an important priority for future colliders

In SM, EWSB occurs at a crossover, but new physics can alter the Higgs potential



$$V = V_{\text{tree}} + \Delta V_{\text{thermal}} + \Delta V_{\text{loop}}$$

Possibilities:

Increase thermal cubic term $\left(\sim \frac{1}{12\pi} g^3\right)$

Decrease effective quartic $\left(\sim \frac{1}{64\pi^2} g^4 \log g^2\right)$

Introduce tree-level cubic couplings $(\sim g^2)$

See e.g. Chung, Long, Wang 2012

Motivation

Models relying on tree-level effects are typically the stealthiest, and thus provide a compelling target for experimental searches.

This talk: **SM + scalar singlet**

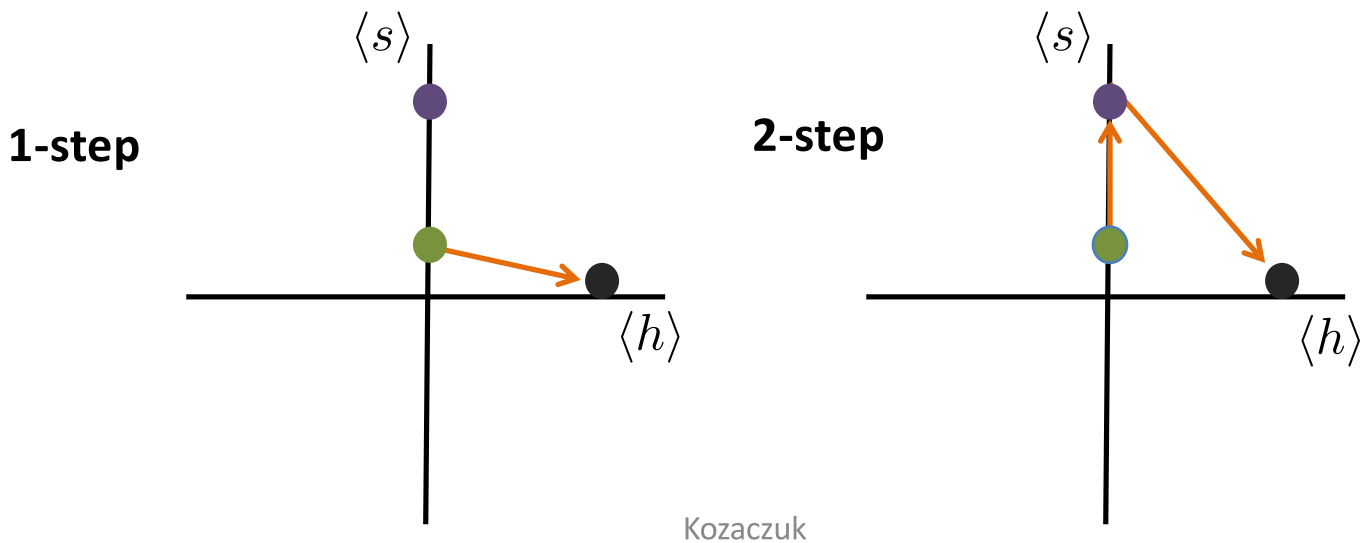
$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

Mass eigenstates:

$$h_1 = h\cos\theta + s\sin\theta$$
$$h_2 = -h\sin\theta + s\cos\theta$$

The EWPT can be strongly first order and proceed in one or two steps

See e.g. Profumo et al, 2007; Espinosa et al, 2011; Curtin et al, 2014, Profumo et al, 2014; Jiang et al, 2015; Xiao + Yu, 2016, …



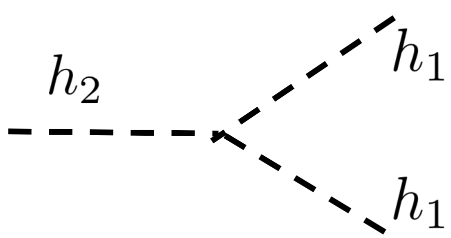
Overview

Signatures at Higgs factories, like CEPC? Look for evidence of new couplings responsible for strengthening the EWPT

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} a_1 |H|^2 S + \frac{1}{2} a_2 |H|^2 S^2 + b_1 S + \frac{1}{2} b_2 S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4$$

→ **Deviations in σ_{Zh}** (present even in the absence of mixing)

→ **Direct production of singlet-like states in exotic Higgs decays** (for light singlets)



Sensitive to new cubic terms in the potential

Note: There are other signals not covered in this talk, e.g. Higgs self-coupling deviations, direct production,…

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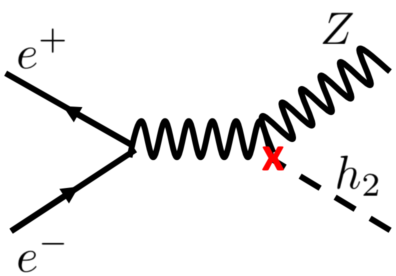
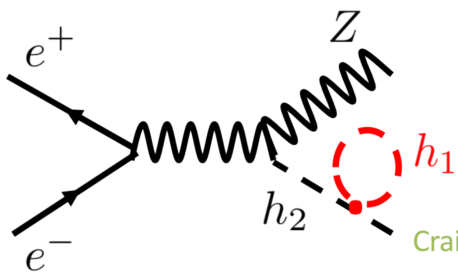
Zh cross-section

The Zh cross-section is affected both by mixing and by the hSS coupling through wavefunction renormalization effects (See also Andrew Long's talk)

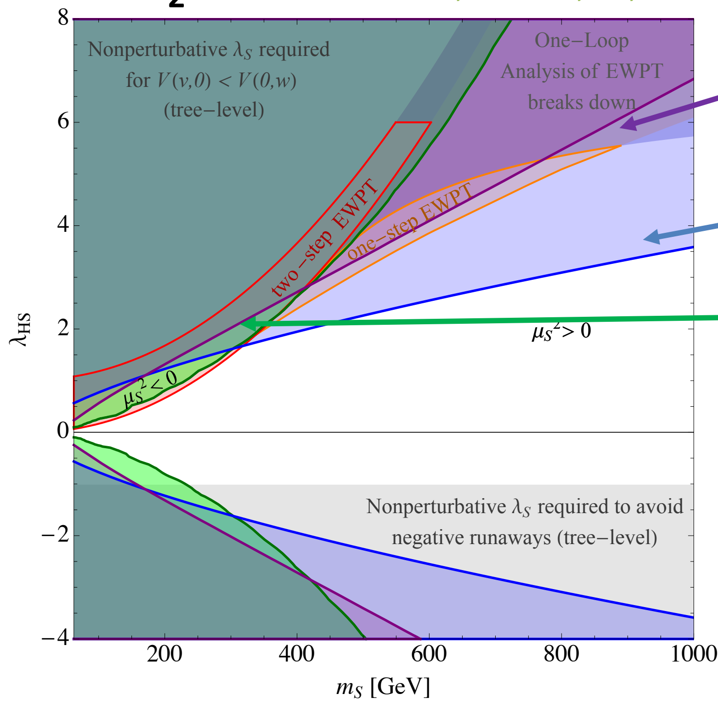




$$\delta_{Zh} = \frac{\sigma_{Zh_1}}{\sigma^{\rm SM}_{Zh_1}} - 1 \approx -\sin^2\theta + \frac{\lambda^2_{221}}{32\pi^2 m_1^2}(1 + F(\tau_s))$$

Craig, Englert, McCullough 2014

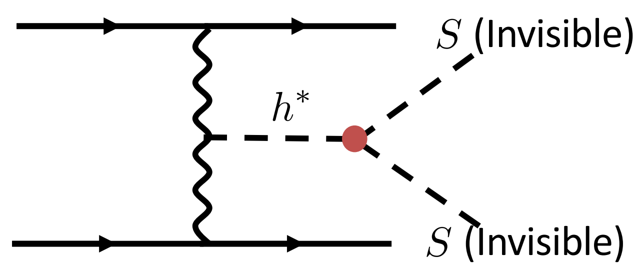
Z_2 limit: Curtin, Meade, Yu, 2014



$e^+e^- \to$ Zh cross-section deviation > 0.6%

Higgs self-coupling deviation > 10%

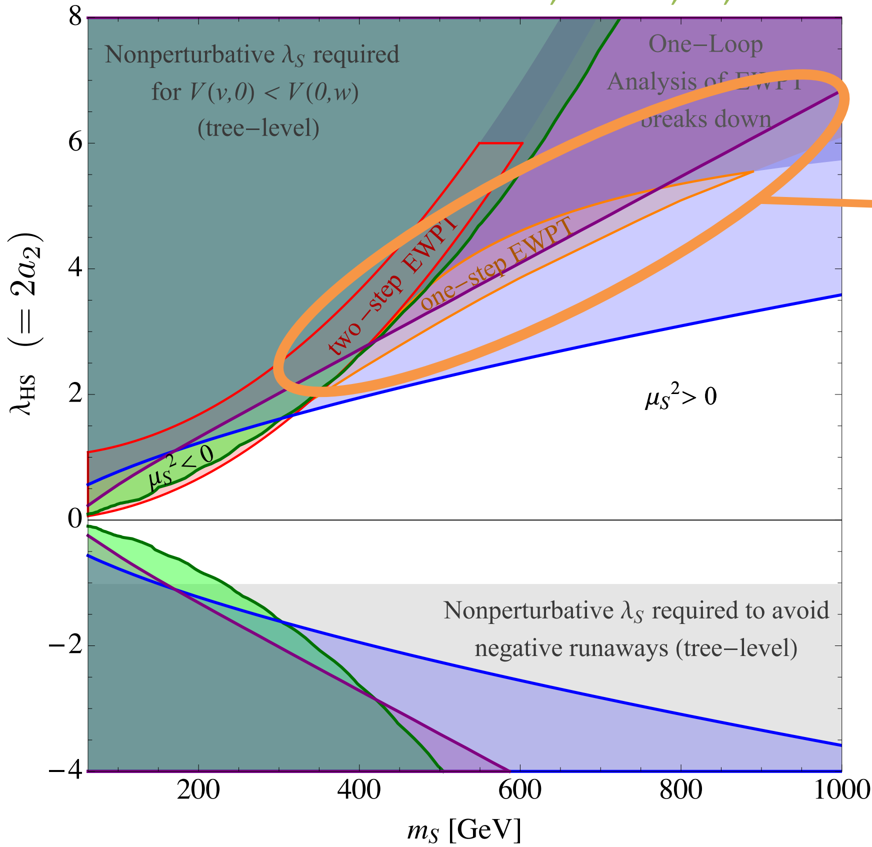
Non-res ss production (30 ab^{-1})



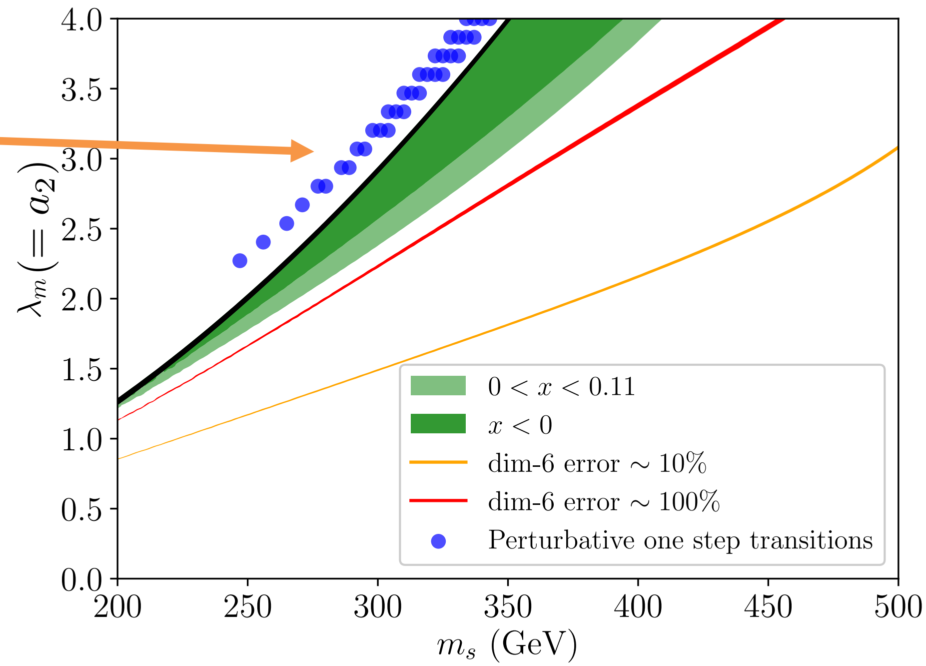
Z_2 Limit: Beyond Perturbation Theory

Important to cross-check against non-perturbative results

Curtin, Meade, Yu, 2014



Gould ,JK, Niemi, Tenkanen, Weir, to appear

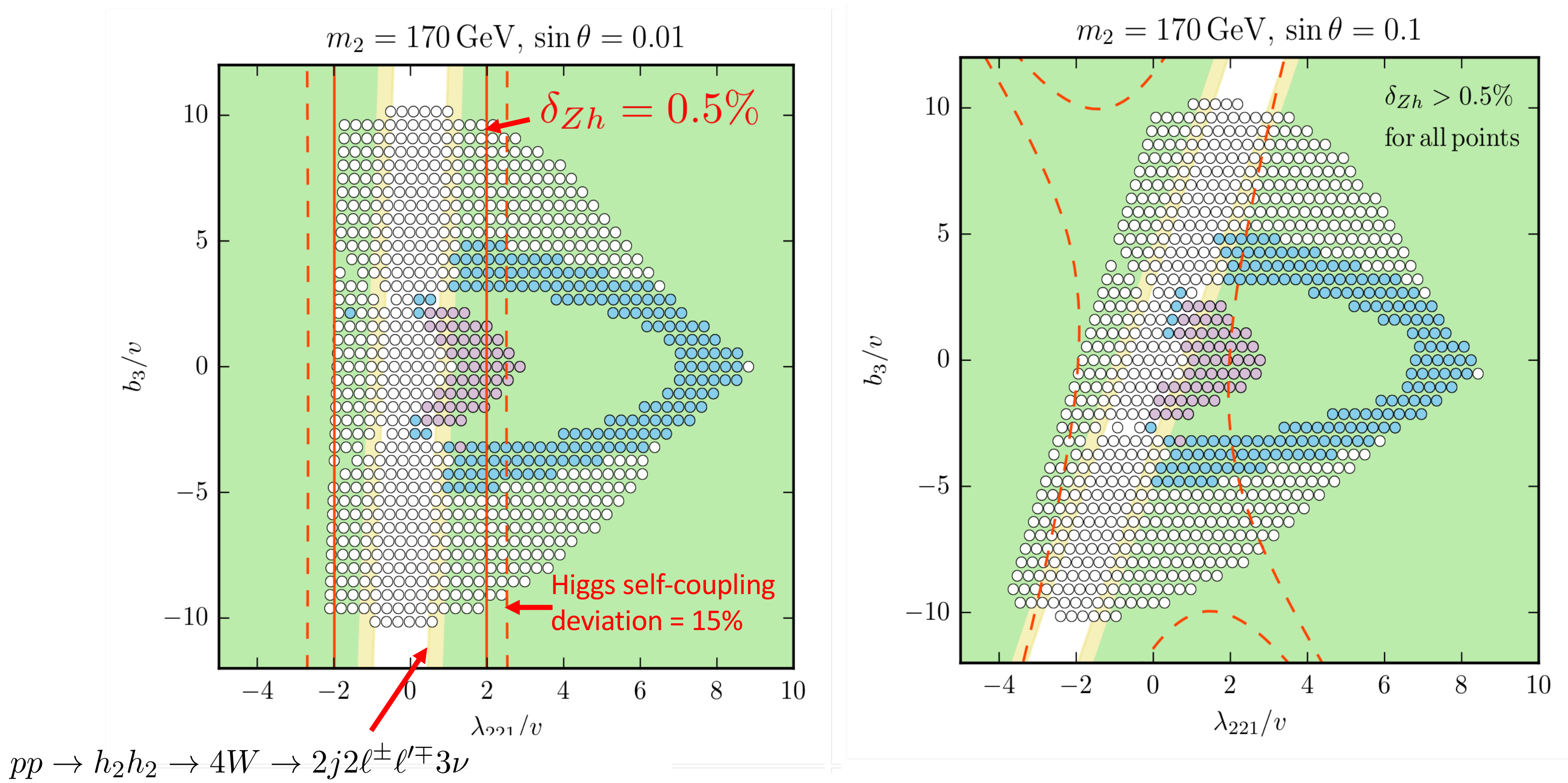


Non-perturbative results agree qualitatively: lower bound on λ_{HS} from requiring first-order EWPT

Zh cross-section beyond the Z_2 limit

Complementarity between Zh and non-resonant double singlet production at 100 TeV pp

From Chen, JK, Lewis, 2017



Zh measurements at CEPC will provide excellent coverage of strong first-order EWPT-compatible parameter space in both the Z_2 and non-Z_2 cases

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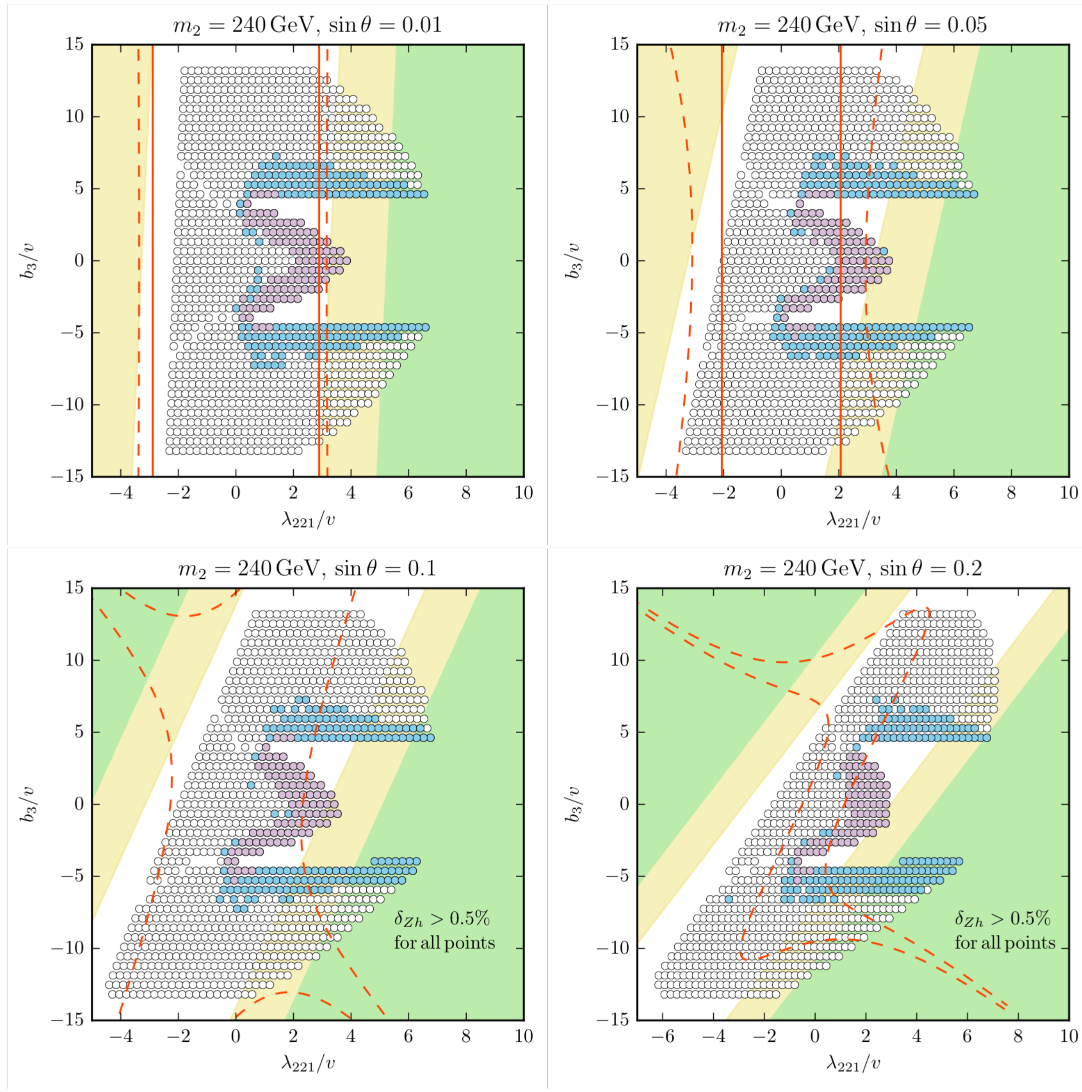
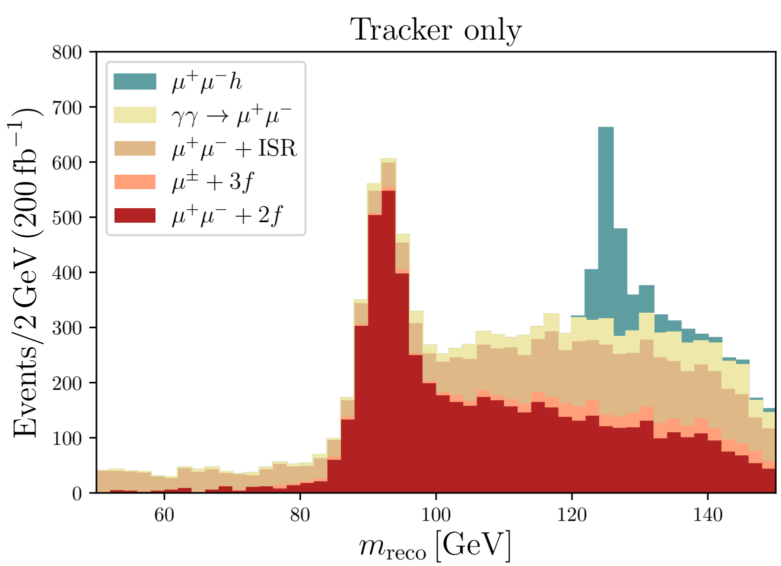


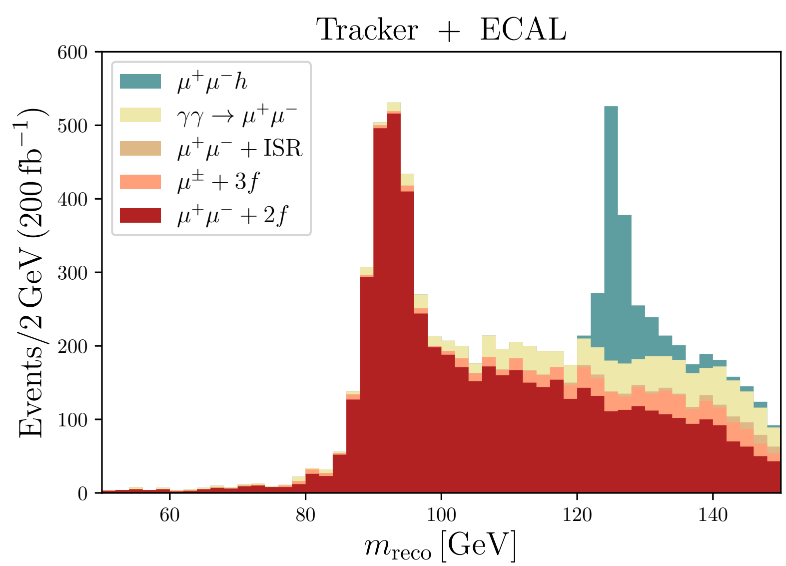
Heavier masses below the di-Higgs threshold more difficult at small mixing, but might be able to close the gap with more sophisticated analysis of non-resonant h_2h_2 production

From Chen, JK, Lewis, 2017

Zh cross-section: a staged approach?

Precise Zh measurements can be achieved even without calorimetry





Muon channel

Tracking only (5.6 ab^{-1}): $\delta\sigma_{Zh} \simeq 1.1\%$

Tracking + calorimetry: $\delta\sigma_{Zh} \simeq 0.9\%$

Work to appear soon with P. Draper and S. Thomas

Also can achieve reasonably efficient electron ID from tracking information alone

Practical applications: initial lower-cost upgradable detector, less costly second detector, ...

Overview

Signatures at Higgs factories, like CEPC? Look for evidence of new couplings responsible for strengthening the EWPT

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

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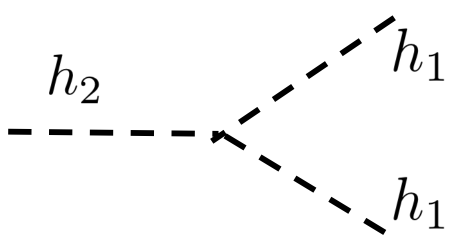


Sensitive to new cubic terms in the potential

Note: There are other signals not covered in this talk, e.g. Higgs self-coupling deviations, direct production,…

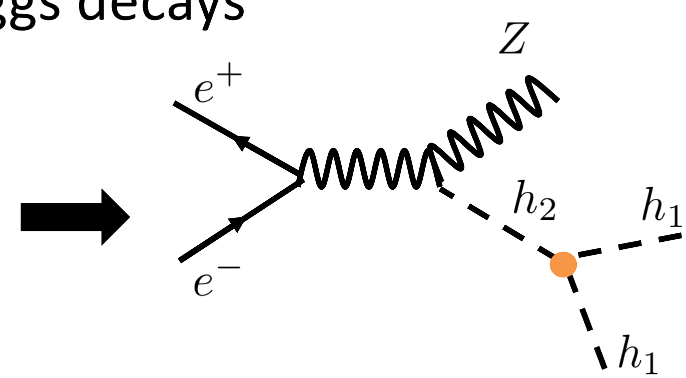
The EWPT and Exotic Higgs Decays

New scalars responsible for strengthening the EWPT can also be light, and therefore accessible through exotic Higgs decays at the CEPC

Scalars living in this mass range are constrained by LEP. Mixing angle must be relatively small ($|\cos\theta| \lesssim 0.05$ is allowed for all masses < 125 GeV)

For small mixing angles, expect a_2 and b_3 to be primarily responsible for strengthening the EWPT. Since a_2 also sets the hSS coupling, there should be a correlation b/t strong EWPTs and exotic Higgs decays

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$



Z_2 limit

Correlation is easy to see in the Z_2 limit: a_2 is the only coupling between S and h, so it cannot be arbitrarily small

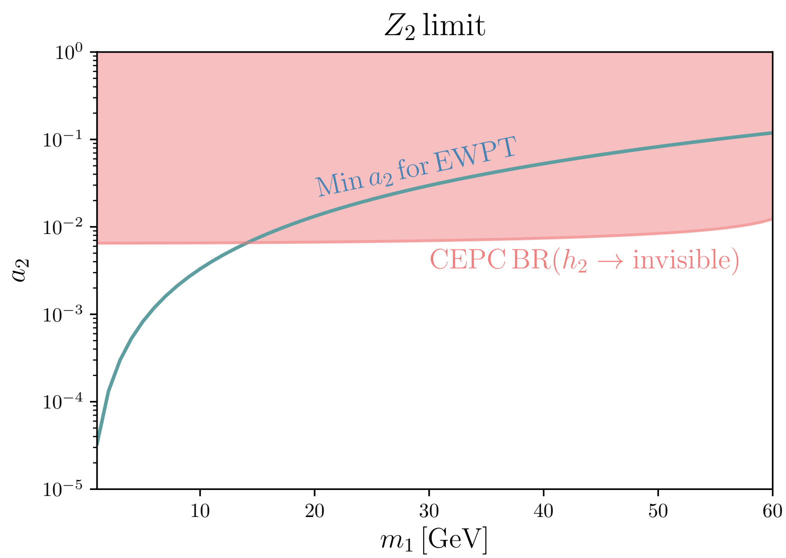
See also Curtin, Meade Yu, 2014; Craig et al, 2014

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} a_1 |H|^2 S + \frac{1}{2} a_2 |H|^2 S^2 + b_1 S + \frac{1}{2} b_2 S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4$$

Necessary condition for strong first-order EWPT: $a_2 > \frac{1}{v^2}\left(2m_1^2 - \frac{b_3^2}{2b_4}\right)$

Provides CEPC target for Higgs → invisible:

Projected CEPC sensitivity taken from Liu, Wang, Zhang 2016



CEPC should be able to probe light invisibly-decaying Higgs portal scalars consistent with a strong EWPT down to ~10 GeV.

Work in progress with M. J. Ramsey-Musolf and J. Shelton

Beyond the Z_2 limit

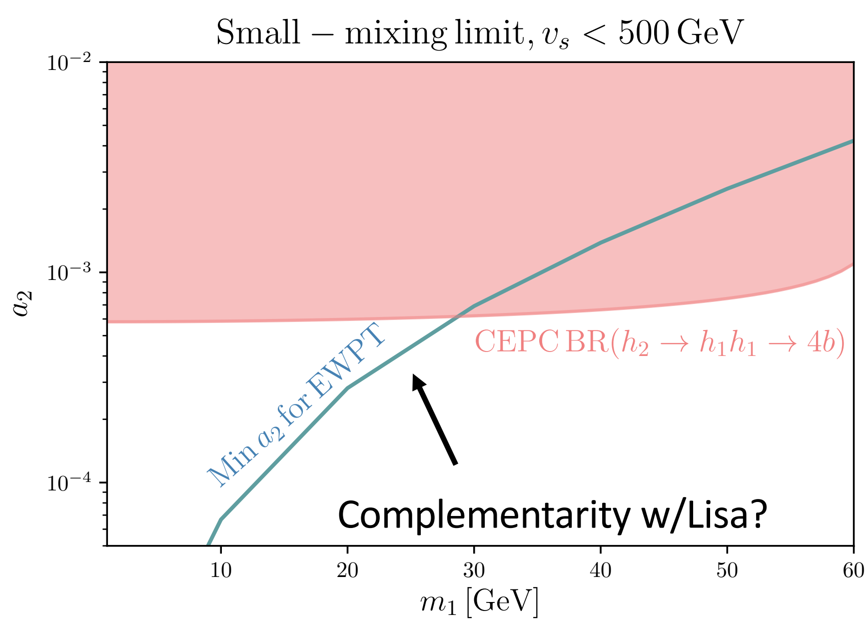
General case more complicated. Simplifies in the small-mixing limit

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

Now b_3 can potentially compensate for small a_2. However, imposing requirements from vacuum stability, completion of the PT, etc still place a lower bound on $BR(h_2 \to h_1 h_1)$:

Larger mixing angles require numerical scans; expect similar conclusions

Projected CEPC sensitivity taken from Liu, Wang, Zhang 2016



CEPC should be able to probe light visibly-decaying scalars consistent with a strong EWPT and other pheno requirements down to ~30 GeV.

Work in progress with M. J. Ramsey-Musolf and J. Shelton

Takeaways

-The CEPC will provide excellent opportunities to probe some of the most elusive models predicting a strong first-order electroweak phase transition

-Zh measurements will access much of the singlet-driven EWPT parameter space with non-negligible mixing, as well as the Z_2 case

-Excellent CEPC tracking resolution provides opportunities for a stage of tracker-only operation without significant loss of physics reach in Zh. A staged approach may be of practical relevance given budgetary constraints.

-Strong EWPTs with light scalars predict concrete targets for exotic Higgs decay searches at the CEPC. It would be worthwhile to map out complementarity with other experiments in this regime (SPPC, LISA,…)

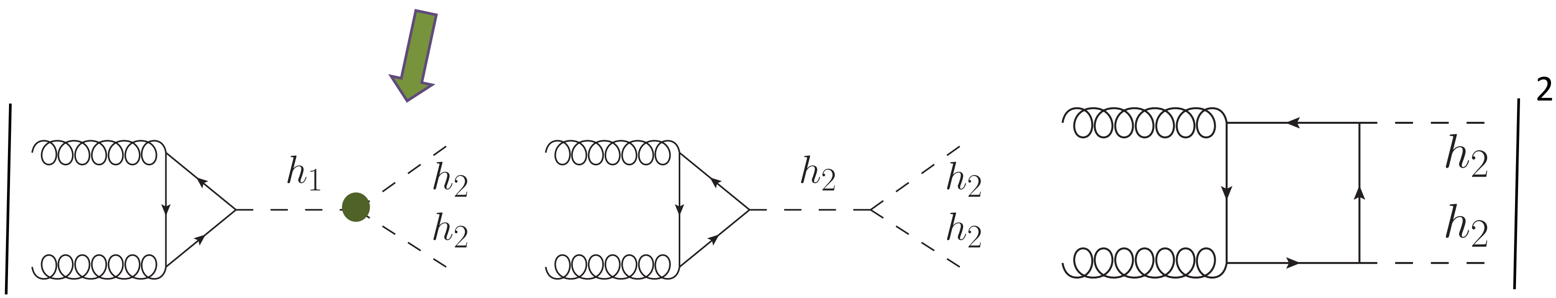
Backup

Non-Z_2 singlets

Expect **singlet-like pair production** to be correlated with the strength of the EWPT Chen, JK, Lewis, 2017

$$V_{\rm cubic} = \frac{\lambda_{111}}{3!}h_1^3 + \frac{\lambda_{211}}{2!}h_2 h_1^2 + \frac{\lambda_{221}}{2!}h_2^2 h_1 + \frac{\lambda_{222}}{3!}h_2^3$$

$$\sigma_{h_2 h_2} \propto$$



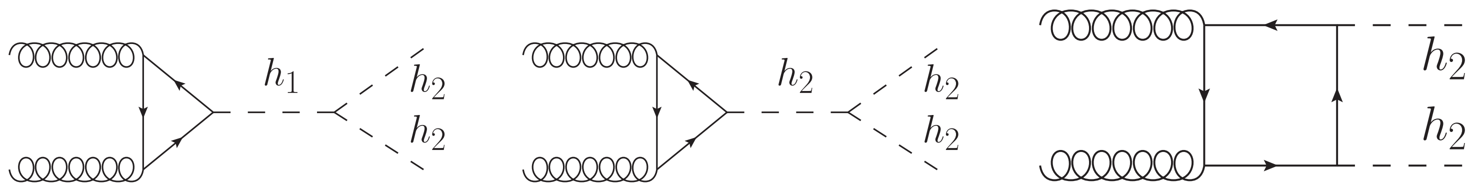
Now the singlet-like state decays visibly. Various final states, but consider trileptons

$$3\ell 3\nu 2j,\ {\rm BR}(h_2 \to WW \to \ell\nu 2j, h_2 \to WW \to 2\ell 2\nu) = 32.41 \times 10^{-4}$$

Familiar channel from pre-Higgs discovery papers
(e.g. Baur, Plehn, and Rainwater, 2002)

Non-Z_2 singlets

Non-resonant singlet-like pair production at the SPPC   Chen, JK, Lewis, 2017



$$pp \to h_2 h_2 \to 4W \to 2j2\ell^{\pm}\ell'^{\mp}3\nu, \qquad \ell \neq \ell'$$

Dominant backgrounds: $t\bar{t},\ WZ,$ rare SM processes (assume fake rate $\epsilon_{j\to\ell} = 10^{-3}$)

Baseline selection:

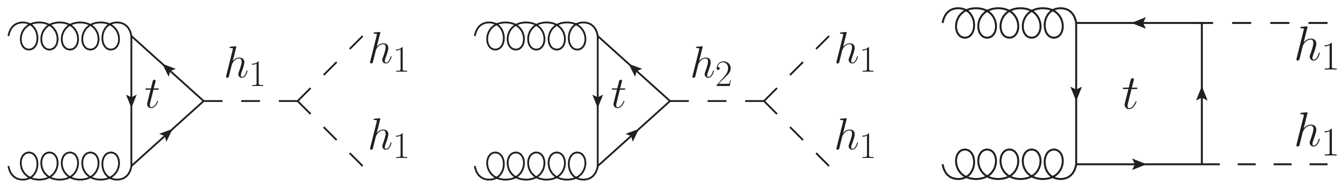
- -3 identified leptons with no OSSF pair
- -At least one jet pair reconstructing to the W mass
- -*MET*>30 GeV
- -b-jet, hadronic tau vetoes

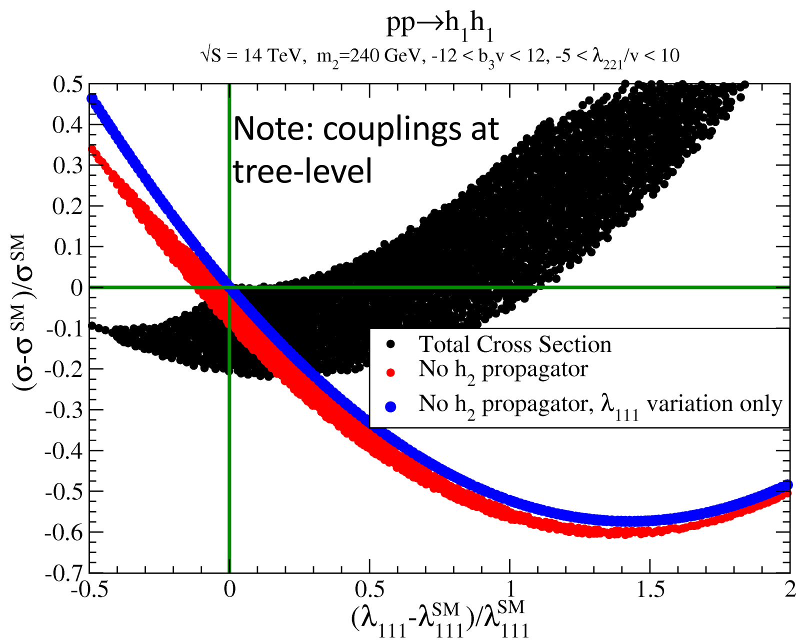
Additional cuts on m_{T2} , $m_T^{\min} \equiv \mathrm{Min}\{M_T(\ell_1, E_T), M_T(\ell_2, E_T), M_T(\ell_3, E_T)\}$
and total invariant mass

Higgs self-coupling revisited

Be careful… in models with additional light scalars, the usual correlation between σ_{hh} and the Higgs self-coupling can break down Chen, JK, Lewis, 2017

Higgs coupling to top quark altered New diagram! Higgs coupling to top quark altered

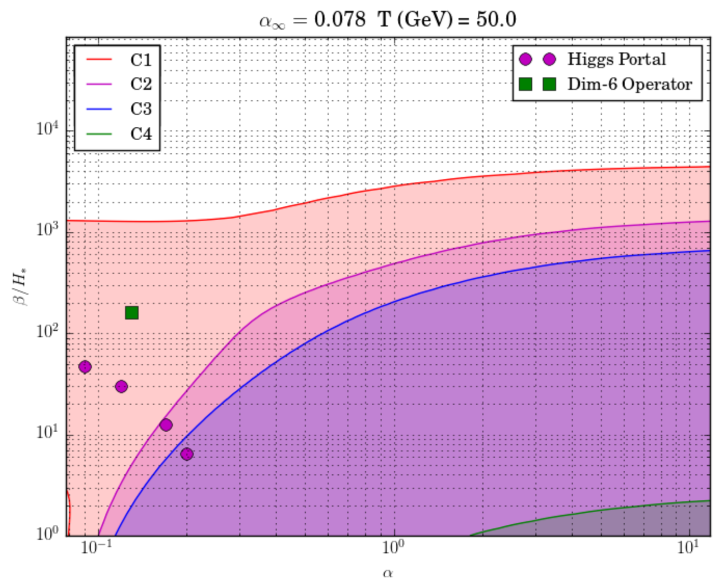




How well can future pp colliders actually determine the Higgs self-coupling in this case? Information about the *hhs* coupling? Can use information encoded in distributions… Study in progress with Ian Lewis

Complementarity with LISA

If a signal is observed, LISA could give direct evidence of a strong first-order phase transition (see also Andrew Long's talk)



Caprini et al, 2015

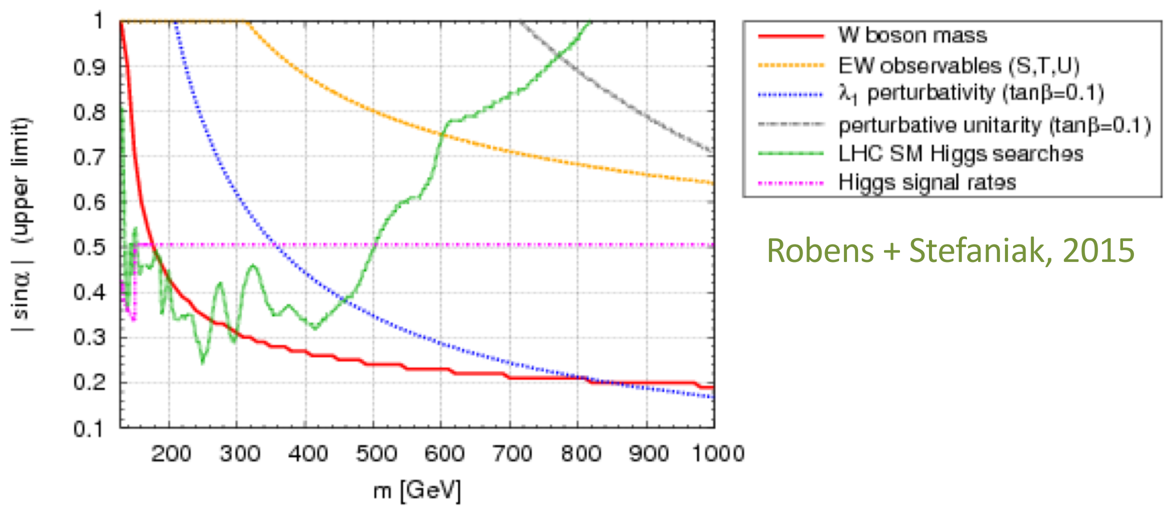
(see also Huang, Long, Wang, 2016)

Status of LISA: chosen by the ESA as the Cosmic Vision L3 experiment. Very active community moving forward with design and science studies. Launch in mid 2030's.

Configuration ~finalized. Stay tuned for update from Cosmology Working Group regarding sensitivity to phase transitions given recent developments

Real Singlet Parameter Space

Lots of phenomenologically viable parameter space



Robens + Stefaniak, 2015

HL-LHC likely to probe down to |sinθ| ~ 0.1 for heavier masses via direct production Buttazzo, Sala and Tesi, 2015

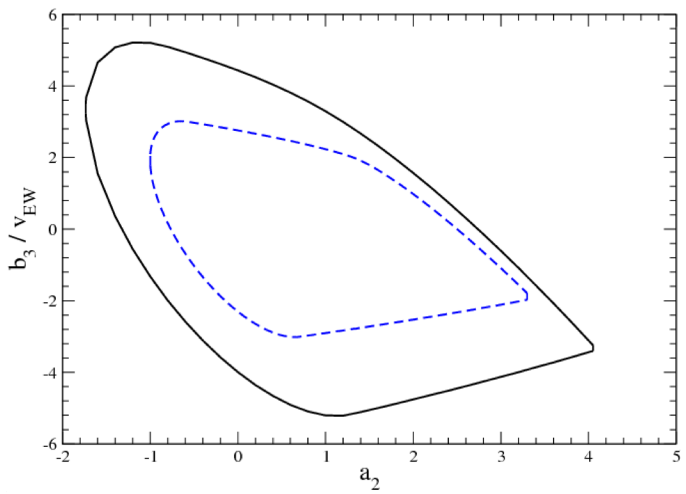
For $m_2 > 2m_1$, resonant di-Higgs will provide additional coverage (provided |sinθ| is not too small) See e.g. No, Ramsey-Musolf, 2013; Chen, Dawson, Lewis, 2014

Small mixing will be difficult

Real Singlet Parameter Space

How can we comprehensively analyze the parameter space?

Choose mass, mixing angle and require correct Higgs mass and VEV. Then scan over all parameter space consistent with 1-loop vacuum stability, perturbativity, and perturbative unitarity → $|a_2|,\ |b_3|/v < 4\pi, \quad b_4 < 8\pi/3$



From Chen, Dawson, Lewis 2014

Marginalize over singlet quartic coupling; include 1-loop corrections